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REPORT ON WORKSHOP ON FLUIDIZED BED COMBUSTION IN CANADA

E.J. Anthony and J.R. Grace

July 1987

Presented at the University of British Columbia, Vancouver, B.C., May 27, 1987.

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41 pp

ENERGY RESEARCH LABORATORIES
DIVISION REPORT ERL 87-60(TR)

MICROMEDIA

REPORT ON WORKSHOP ON FLUIDIZED BED COMBUSTION IN CANADA

by

E.J. Anthony* and J.R. Grace**

ABSTRACT

A one day workshop on fluidized bed combustion (FBC) was organized at the University of British Columbia prior to the 1987 Spring Technical Meeting of the Combustion Institute because many of Canada's leading combustion specialists would be in Vancouver during this period. Sixteen speakers from across Canada spoke on various aspects of FBC technology; three site visits were also conducted to the University of British Columbia (UBC)pilot plant circulating fluidized bed combustion (CFBC) unit, the cold model CFB facility and the spout-fluid bed combustor and high pressure gasifier at B.C. Research. The audience included representatives from a number of the major petrochemical and engineering consulting companies and Canadian universities.

This report provides a permanent record of the event including a short summary of the presentations, together with a list of papers prepared for, or distributed at, the workshop. The morning and afternoon sessions were chaired by Professor John Grace of UBC and Dr. E.J. Anthony of CANMET, respectively. Copies of papers distributed from UBC affiliates may be obtained from Professor Grace and any others may be obtained from Dr. Anthony or the authors.

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COMPTE RENDU D'UN ATELIER SUR LA COMBUSTION EN LIT FLUIDISÉ AU CANADA

par

E.J. Anthony* et J.R. Grace**

RÉSUMÉ

Un séminaire sur la combustion en lit fluidisé (CLF) a eu lieu à l'Université de la Colombie-Britannique. Le séminaire, qui a duré une journée, a été tenu avant la réunion technique du printemps du Combustion Institute parce que plusieurs experts canadiens en combustion se trouvaient à Vancouver à ce moment là. Seize orateurs représentant toutes les régions du Canada ont présenté les diverses facettes de la technique de combustion en lit fluidisé. Trois visites ont également été organisées pour l'observation sur place de l'unité de combustion à lit fluidisé circulant de l'usine-pilote de l'Université de la Colombie-Britannique (UCB), d'un modèle non chauffé de l'installation CLF et de la chambre de combustion à lit fluidisé jaillissant et du gazéificateur sous pression de B.C. Research. L'auditoire était composé de représentants des universités canadiennes et des plus importants bureaux d'études techniques et pétrochimiques.

Le compte rendu constitue un dossier permanent de l'événement. Il comprend également un bref résumé des présentations de même qu'un répertoire des communiqués scientifiques préparés à l'occasion du séminaire et distribués le jour même. Les séances de la matinée et de l'après-midi étaient dirigées par M. John Grace, professeur à l'UCB et M. E.J. Anthony, de CANMET. On peut obtenir des exemplaires des documents distribués par l'intermédiaire des sociétés affiliées à l'UCB, en contactant le professeur Grace. Les autres documents peuvent être obtenus en communiquant avec M. Anthony ou l'un des auteurs.

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INTRODUCTION

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SUMMARIES OF PRESENTATIONS

1. OVERVIEW OF UBC ACTIVITIES IN FLUIDIZED BED COMBUSTION AND RELATED FIELDS

by J.R. Grace, University of British Columbia

The Department of Chemical Engineering at UBC has been very active in research on fluidized beds (gas-solid, liquid-solid, three-phase) and spouted beds for many years. Extensive work on circulating fluidized beds has been carried out in the past five years. Faculty members in the department also have broad general expertise in other aspects of fluid-particle systems. Eight faculty members (Bowen, Brereton, Epstein, Grace, Kerekes, Lim, Meisen and Watkinson) have formed a "Fluid-Particle Research Group" and have an Infrastructure Grant to assist with cooperative research projects.

Research in gasification and combustion in fluidized and spouted beds has been ongoing for the past decade. This work is both fundamental and applied. A list of current and very recently completed projects is attached. Altogether the research involves:

8 faculty members
10 research associates, post-doctoral fellows and visiting scholars
15 graduate students
9 undergraduates

Work has been supported by 12 different organizations. Equipment ranges from bench- to pilot-plant scale (up to 0.9 m diam) as follows:

8 conventional fluidized beds
9 spouted beds and spout-fluid beds
3 circulating fluidized beds

The department believes strongly in doing work which is relevant to practical needs and problems. They welcome enquiries regarding joint or sponsored research projects.

UBC DEPARTMENT OF CHEMICAL ENGINEERING
ACTIVITIES IN FLUIDIZED BED COMBUSTION AND RELATED AREAS

(a) CIRCULATING FLUIDIZED BEDS

Topic	Type of project	Principal worker	Supervisor	Support
Hydrodynamics of circulating fluidized beds*	Ph.D	C. Brereton	JRG	NSERC, Studsvik
Solids mixing in circulating beds*	Ph.D	W. Goldblatt	JRG	NSERC
Combustion of tar and pitch in a circulating fluidized bed*	Contract	H. Li et al ≠	CJL,JRG	EMR, NSERC, Env.Can. Polymath
Control of NO_x and SO_2 emissions from circulating fluidized bed combustors*	Ph.D	J. Zhao	CJL,JRG	NSERC
Measurement of solids circulation rates in CFB	M.Sc B.Sc	J. Burkell ≠ D. Hopkins ≠	JRG J.Zhao	NSERC
Use of oxygen probes in CFBC	B.Sc	K. Hakansson ≠	CJL	Dept.
Gas mixing in CFB units*	B.Sc	J. Yu ≠	CMHB JRG	Dept.
Hydrodynamics and chemical reaction of aerogel particles in CFB reactors	Postdoc	R. Legros	JRG CMHB	NSERC
Heat conduction in membrane waterwall cooling surfaces	-	M. Fournier ≠	B.Bowen JRG	EMR NSERC
Concentric circulating fluidized bed	M.Sc	I. Fusey ≠	CJL,	NSERC
(b) LOW VELOCITY FLUDIZED BEDS				
Erosion of horizontal tubes	Ph.D	J. Zhu	CJL,JRG	NSERC
Influence of particle size distribution on fluidized bed hydrodynamics	M.Sc	T. Ip	JRG G.Khoe	PRF
Influence of particle size distribution on chemical reaction in fluidized beds	Chinese scholar	G. Sun	JRG	PRF

(b) LOW VELOCITY FLUIDIZED BEDS (Cont'd)

Topic	Type of project	Principal worker	Supervisor	Support
Fluidized bed reactor model verification on an industrial scale reactor	Visitor	J. Johnsson	JRG	NSERC Badger
Integrated retorting-combustion system using fluidized bed technology	Contract	-	APW,CJL	Polymath
Flow visualization around horizontal tubes*	B.Sc	P. Williams ≠	J. Zhu, JRG	Dept.
Fluidized bed drying of wood wafers	Ph.D	F. Laytner	NE,JRG, KLP	Dept. MacBlo
Three-phase fluidization of porous particles	B.Sc	D. Lee	NE,JRG	Dept. Challenge '87
Fluidized bed Claus reactor	Ph.D	E. Besher	AM	NSERC
Fluidized bed incineration of simulated hazardous organics	B.Sc	G. Kerfoot≠	K.C. Teo	Dept.
Horizontal jet penetration in fluidized beds	B.Sc	M. Krause≠	JRG	Dept.
(c) SPOUTED BEDS AND SPOUT-FLUID BEDS				
Combustion in spouted and spout-fluid beds		G. Khoe≠ S. Low	CJL,NE JRG, APW	BCSciC Esso
Modelling of spouted and spout-fluid bed combustors	M.Sc	J. Zhao≠	CJL,JRG	NSERC
Spouted bed coal gasification of coal		T. SueAQuan≠	APW,CJL	EMR,NSERC, SNC, China
Hot gas cleanup of gasification products	Contract	Various	APW	EMR
High temperature spouted bed hydrodynamics	M.Sc	S. Wu≠	CJL,NE	NSERC
Coal comminution and drying in spouted bed	M.Sc	J. Sun	NE,CJL	NSERC
Hydrodynamics of 3 ft. dia. spouted bed	Summer	A. Townson	CJL,JRG	NSERC

(c) SPOUTED BEDS AND SPOUT-FLUID BEDS (Cont'd)

Topic	Type of project	Principal worker	Supervisor	Support
Pyrolysis of coal in a spouted bed	-	G. Rovero≠	APW	BCSciC
Modelling of spouted bed coal gasifier	B.Sc	K. Lee J. Lucas	CJL,APW	Dept.
Fluid dynamic modelling of spouted bed	Ph.D	R. Krzywanski	NE	NSERC
High pressure spouted bed hydrodynamics	-	T. SueAQuan	CJL	NSERC
Drying of coal-oil agglomerates in a spouted bed	Contract	S. Wu	CJL	AlbRC

* Discussed at workshop
≠ Recently completed

Supervisor abbreviations: CMHB - C. Brereton, NE - N. Epstein, JRG - J. Grace, CJL - J. Lim, AM - A. Meisen, KLP - K. Pinder, APW - P. Watkinson

Support abbreviations:
AlbRC - Alberta Research Council;
Badger - Badger Engineering, USA;
BCSciC - B.C. Science Council;
EMR - Energy, Mines and Resources;
Env Can - Environment Canada;
Esso - Esso Resources;
MacBlo - MacMillan Bloedel Ltd.;
NSERC - Natural Sciences and Engineering Research Council of Canada;
Polymath - Polymath Energy Consultants;
PRF - Petroleum Research Fund;
SNC - SNC Inc., Montreal;
Studsvik - Studsvik Energiteknik, Sweden;
Dept. - UBC Dept of Chemical Engineering;
China - Peoples Republic of China.

2. CIRCULATING FLUIDIZED BED HYDRODYNAMICS AND GAS MIXING

by Clive Brereton, University of British Columbia

The fluid mechanics of circulating fluidized beds involve complicated interaction between developing turbulent flows of gas and solids. The flows are affected by boundary layer phenomena, solids aggregation phenomena and contain both microscale and macroscale circulation patterns. Rigorous solutions to the fluid mechanical equations are not

available, and it is even difficult to formulate the equations themselves. However, it is still possible to go about the process of design because a large number of the important mechanical design parameters are related to a single macroscopic fluid mechanical descriptor, that is, the suspended solids density profile. This can be correlated and used, to calculate such parameters as pressure drops, heat transfer coefficients, load following capability, and recycle rates.

General practice has been to correlate density profiles in terms of:

- solids circulation rate,
- gas velocity,
- solids properties (size, density),
- gas properties (density, viscosity).

This is satisfactory if geometric similarity is maintained in scale up and the impact of scale is accounted for. However, this form of correlation neglects an essential aspect of CFB fluid mechanics which hitherto has not been addressed - exit geometry. Studies of a number of exits in the UBC cold model circulating bed (0.15 m ID x 10 m high) have shown that this can be used as an internal separator in the CFB to control internal solids mixing and the ratio of internal to external circulation rates. This affords a unique possibility for optimization of the CFB for a specific purpose, if it can be shown to be valid on a large-scale unit.

Finally, the development of circulating bed density profiles has been studied microstructurally. This has given insight into why a circulating bed behaves as it does, and into potential modifications for improved future design.

NOTES ON CIRCULATING FLUIDIZED BED HYDRODYNAMICS - THE PROBLEM:

- Description of a two-phase non-homogeneous flow involving circulation on microscales and macroscales, boundary layer phenomena, solids aggregation effects, turbulence, and other complexities.
- Rigorous description implausible at present
- What do we need to know for design purposes?
  (a) on the macroscale
  (b) on the microscale

MACROSCOPIC FACTORS RELATING TO HYDRODYNAMICS:

(1) pressure drop

(2) heat transfer coefficients

(3) variation of heat transfer coefficients with gas velocity (load following capacity)

(4) external solids circulation rate (size of recycle system)

(5) numerous others

All of the above can be related to the suspended solids density profile.

SUSPENDED SOLIDS DENSITY PROFILE IS A FUNCTION OF:

(1) solids circulation rate

(2) gas velocity

(3) solids properties (size, density)

(4) gas properties (density, viscosity)

Current industrial correlations employ these variables and assume (enforce) geometric similarity between pilot and full scale units with respect to certain geometric details to eliminate (minimize) the impact of unknowns.

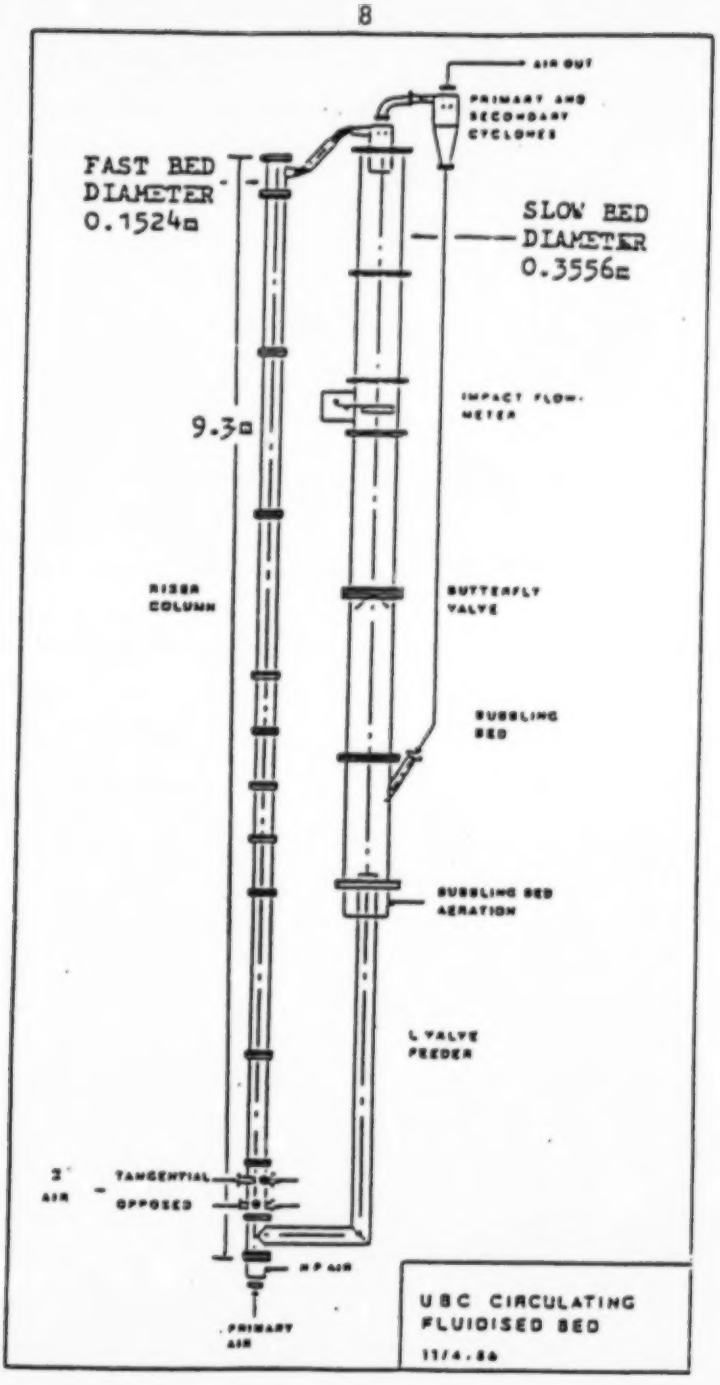
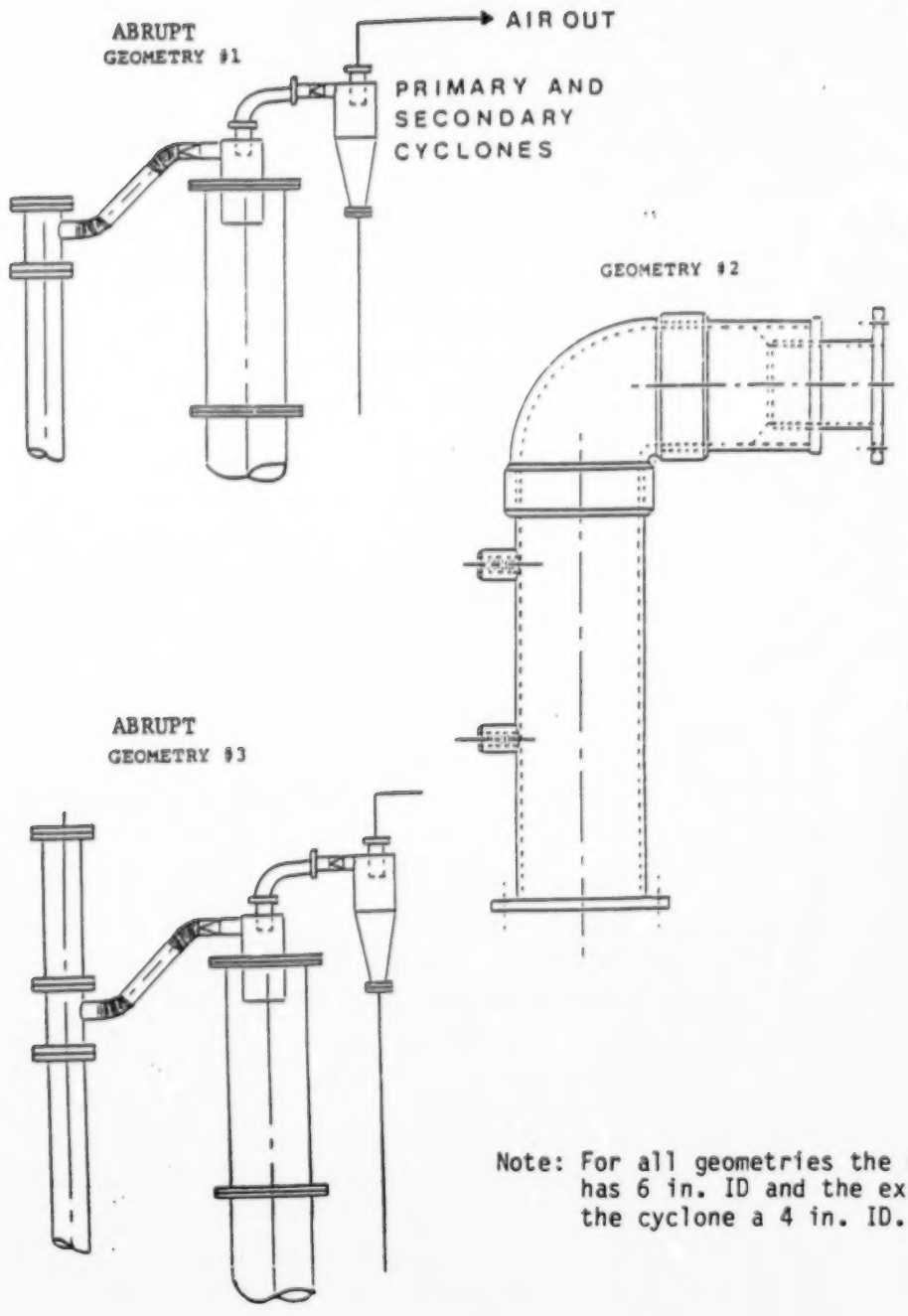


Fig. 1 - Diagram of UBC cold model CFB experimental facility



Note: For all geometries the riser has 6 in. ID and the exit to the cyclone a 4 in. ID.

Fig. 2 - Diagram of exit geometries

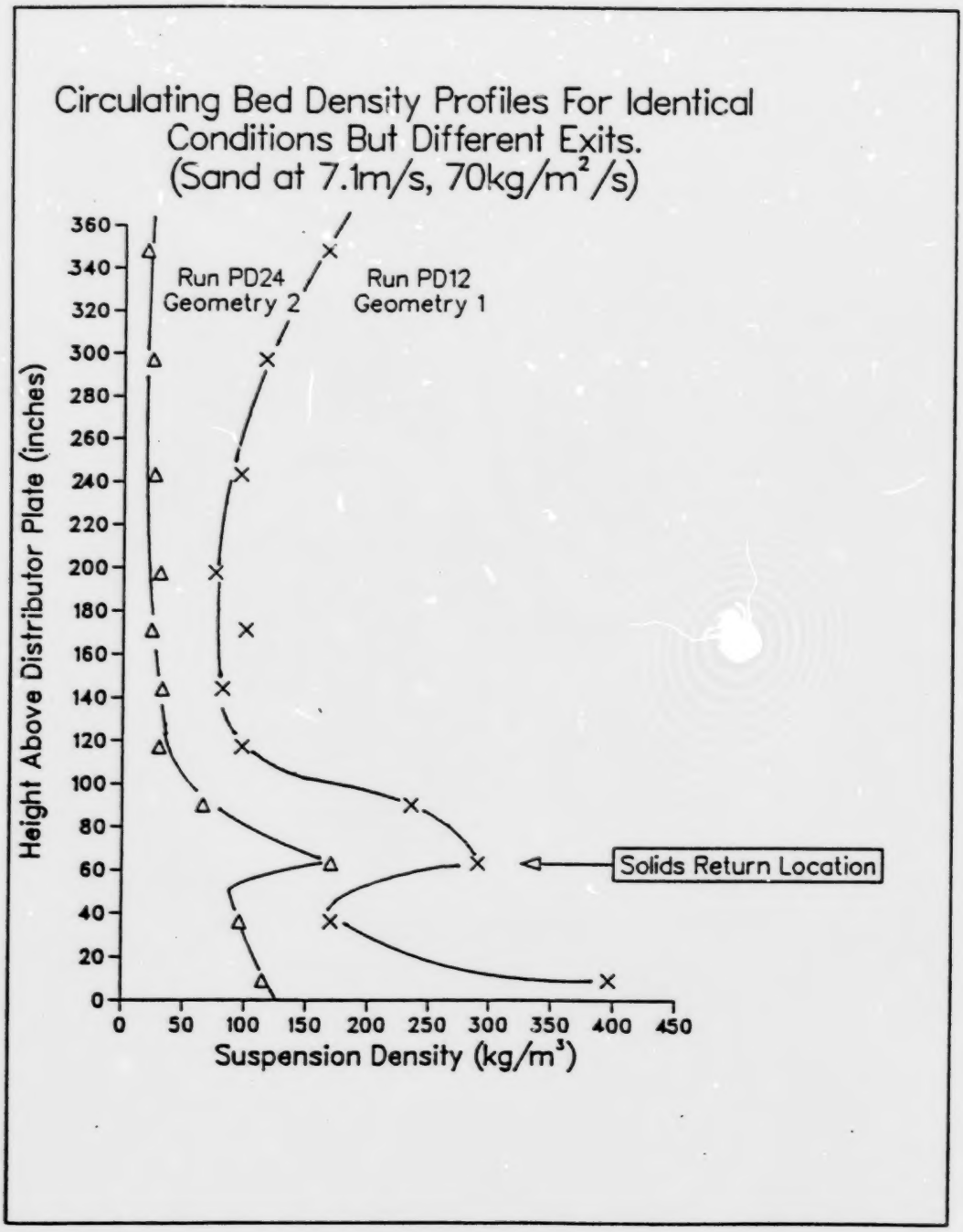


Fig. 3 - Circulating bed density profiles as a function of height above the distributor

EXIT GEOMETRY EFFECTS AND USES

Smooth Exit - promotes high solids circulation rate (external) with a uniform Radial Time Distribution or RTD (plug flow) at a low pressure drop (see Figure 2, Geometry 2)

- ideal for certain catalytic reactions involving catalyst deactivation, e.g., fluid catalytic cracking

- also suited for flash pyrolysis

Abrupt Exit - promotes vigorous internal solids mixing and high uniform suspension densities at low external solids circulation rates

- ideal for minimizing recycle loop sizes and maximizing temperature uniformity and heat transfer in certain CFB combustion systems (see Figure 2, geometry 1 and 3)

Immediate - intermediate mixing, circulation rate, suspension density characteristics

- ideal for combustion units requiring external heat transfer for control purposes, e.g., certain Lurgi units require high external solids fluxes but also require good internal mixing for combustion efficiency

Reference

2.1 Brereton, C., Ph.D Dissertation, UBC, Vancouver, 1987.

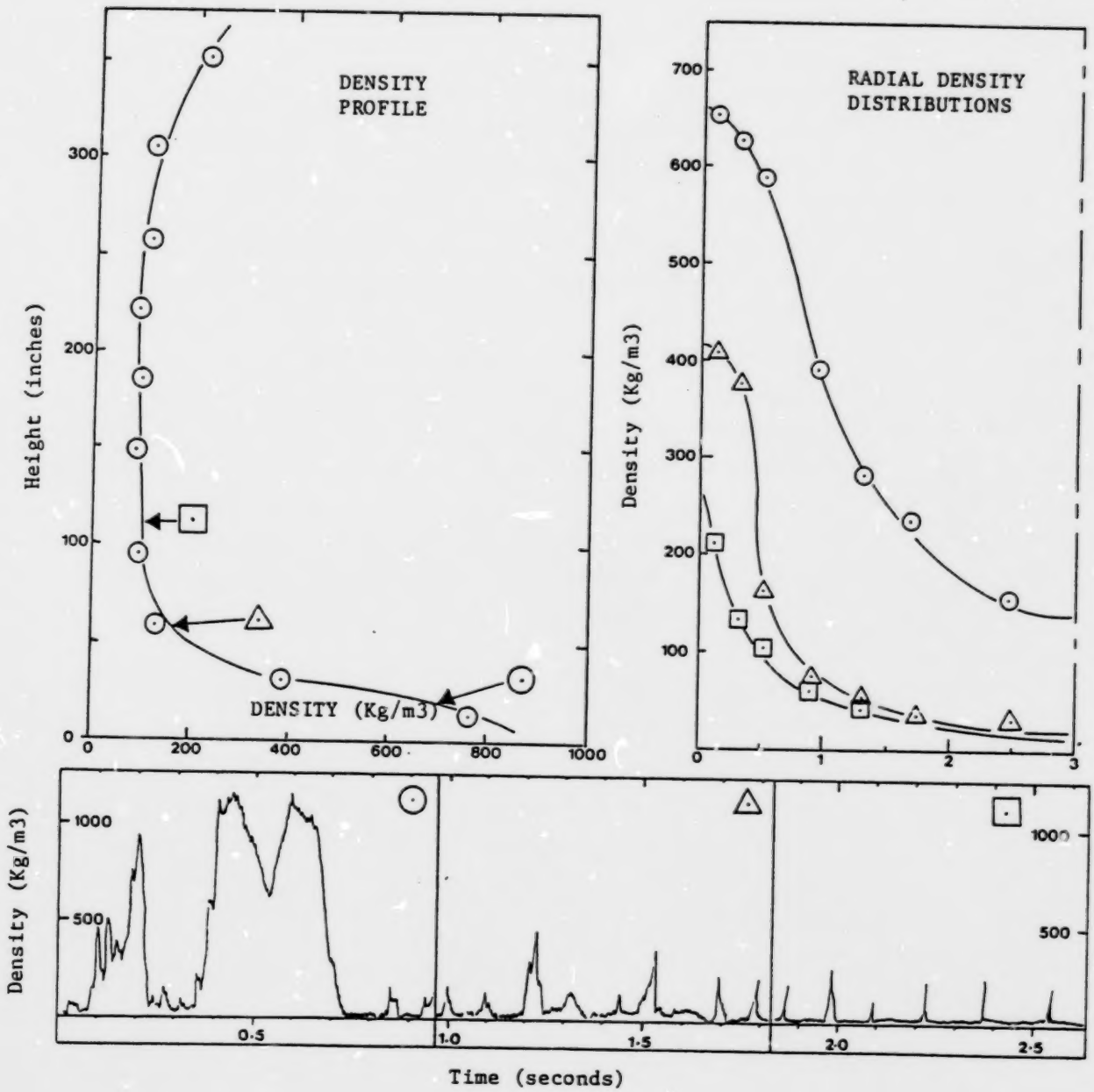


Fig. 4 - Instantaneous density variations (centreline)

3. SOLIDS MIXING IN CIRCULATING FLUIDIZED BEDS

by William Goldblatt, Ph.D Student, University of British Columbia

Evidence from entrained fluidized beds indicates that particle passage through a particle suspension is determined by more than just the particle's properties. In its passage through a fast fluidized bed, a particle apparently experiences different regimes, in which it may be either travelling alone or with other particles, probably mostly the latter. The particle's interaction with the gas, in terms of slip velocity for example, is very different from one regime to another. The purpose of this research is to elucidate the particle's trajectory using a novel technique which registers its velocity at specific locations along the column. Thereafter, statistical inferences can be made regarding the structure of recirculating cells, the average velocity at various radial positions along the column, and how the passage is divided between core and annulus flows. Some early findings using simpler experimental techniques (gas helium tracers and coloured tracer particles) were also described briefly.

References

3.1 Goldblatt, W. "Research proposal - Motion of particles in the fast fluidized regime", UBC, 1984.

3.2 Roberts, C. "The residence time distribution of solids in a fast fluidized bed, B.Sc Thesis, UBC, 1986.

4. HEAT TRANSFER IN CIRCULATING FLUIDIZED BEDS

by Richard Wu, University of British Columbia

Circulating fluidized beds are beginning to penetrate a significant fraction of the market for large-scale steam boilers because of their ability to burn a wide variety of solid fuels with low pollutant emissions and good turndown. Knowing how the heat transfer coefficient between gas-solid suspensions and cooling surfaces varies with operating conditions is critical to the operation of CFB boilers, since turndown is commonly achieved by varying the suspension density in the unit (4.1). The heat transfer area necessary also depends on the heat transfer coefficients which can be achieved at membrane waterwalls in the fast fluidized bed reactor in the region above the secondary air ports. For large units, membrane surfaces may also be suspended in the interior from

above or from the side, and it is again essential to be able to estimate heat transfer coefficients.

Despite the importance of this subject, experimental data are few. Moreover, most of the available data (4.2) are for very small heat transfer surfaces suspended within the interior of small-scale columns operated at room temperature. Recently, data on heat transfer to membrane wall surfaces were obtained in a pilot scale CFB unit at UBC (Fig. 5). Superficial gas velocity was varied from 4 to 7 m/s with solid flux from 7 to 40 kg/m^2 s and bed temperature from 150°C to 400°C. Results have been obtained for 188 and 356 μm sand. The secondary/primary air ratio was varied from 0 to 1.5. These conditions are closer to industrial practice than those reported previously.

Heat transfer coefficients, averaged over 1.53 m of the membrane waterwall surfaces, depend strongly on suspension density (Fig. 6 and 7), but show almost no separate dependence on gas velocity (Fig. 8), bed or suspension temperature (Fig. 9), or secondary to primary air ratio for the conditions studied. For the surface nearest the top of the unit, the coefficient decreases with distance measured downwards from the top, suggesting that particles travel downward along the surface. As a result, average coefficients are lower and the influence of particle size less than for previously reported CFB heat transfer measurements when smaller heat transfer surfaces were employed (Fig. 10).

References

4.1 Kobro, H. and Brereton, C. "Control and fuel flexibility of circulating fluidized beds", in Circulating Fluidized Bed Technology, ed. P. Basu, Pergamon, Toronto, pp. 263-272, 1986.

4.2 Grace, J.R. "Heat transfer in circulating fluidized beds", in Circulating Fluidized Bed Technology, ed. P. Basu, Pergamon, Toronto, pp. 63-80, 1986.

4.3 Fraley, L.D., Lin, Y.Y., Hsiao, K. and Solbakken, A. "Heat transfer coefficient in circulating bed reactor", ASME Paper 83-HT-92, Seattle,1983.

4.4 Kiang, K.D., Liu, K.T., Nack, H. and Oxley, J.H. "Heat transfer in fast fluidized beds", in Fluidization Technology, 2:471-483, ed. D.L. Keairns, Hemisphere, Washington, 1976.

4.5 Mickley, H.S. and Trilling, C.A. "Heat transfer characteristics of fluidized beds", Ind Eng Chem, 41:1135-1147, 1949.

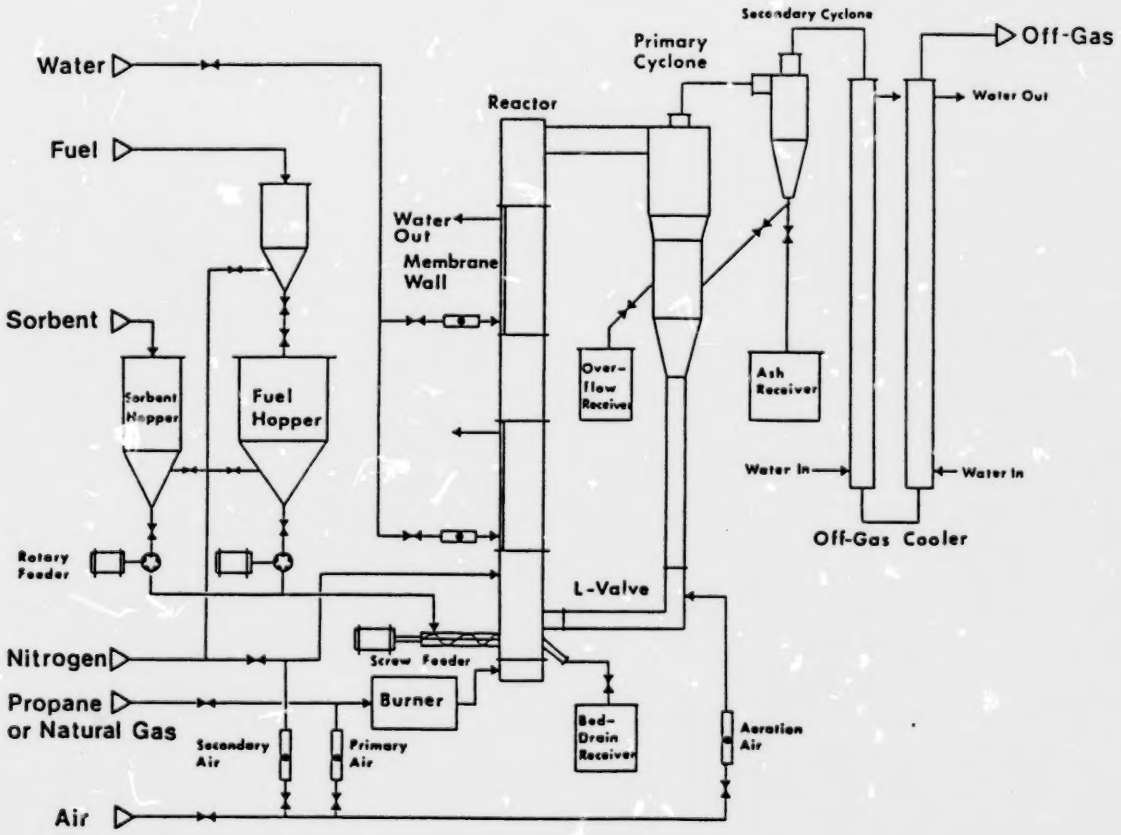


Fig. 5 - Schematic of the pilot scale circulating fluidized bed facility

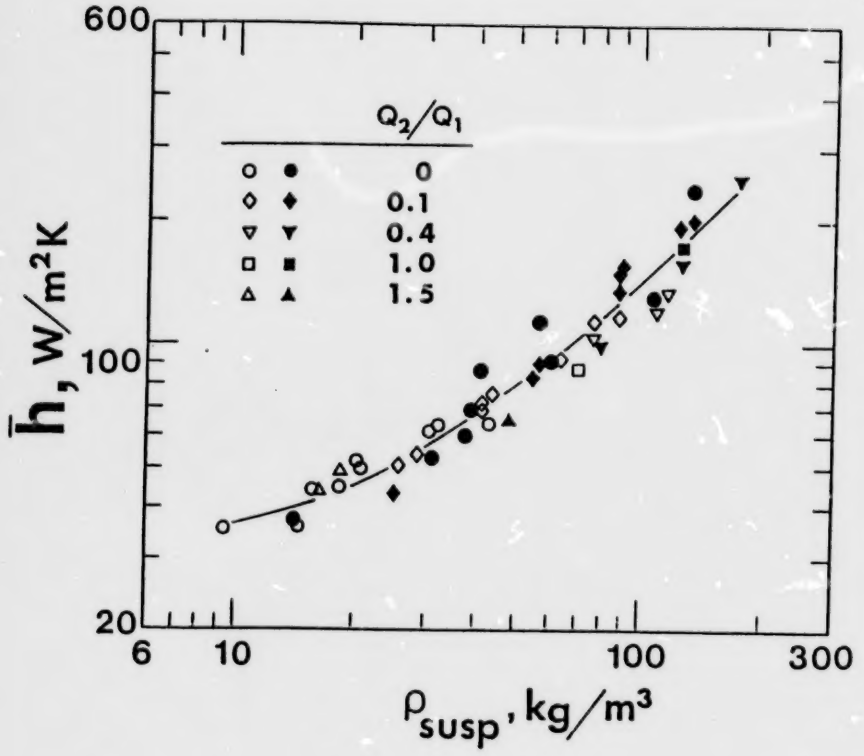


Fig. 6 - Average heat transfer coefficient for membrane wall surfaces for 188 μm sand as a function of suspension density. Open and filled symbols refer to upper and lower exchange surfaces respectively.

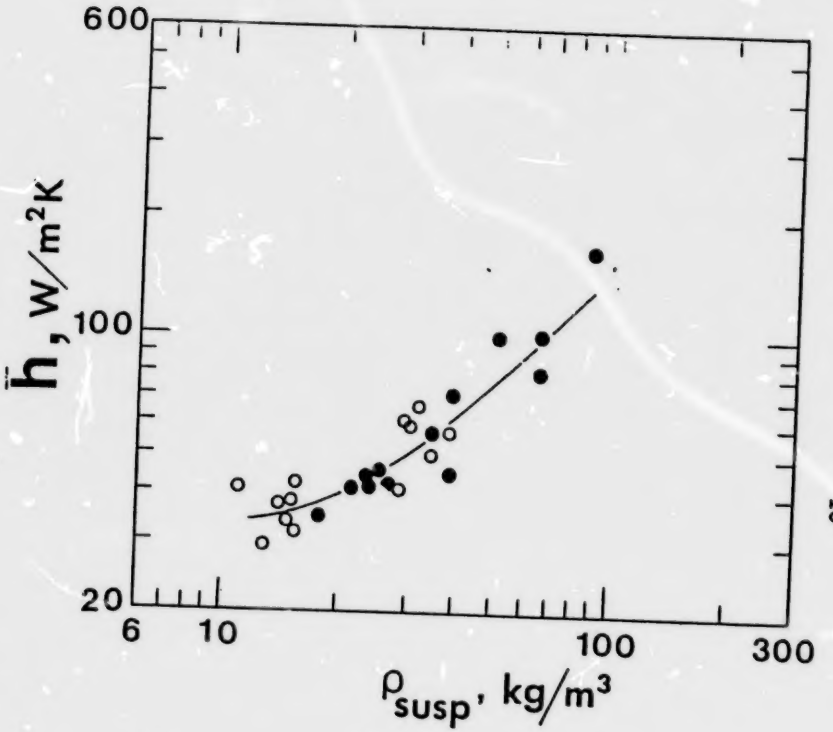


Fig. 7 - Average heat transfer coefficient for membrane wall surfaces for 356 μm sand as a function of suspension density. Open and filled symbols refer to upper and lower exchange surfaces respectively. Secondary to primary air ratio = 0 in all cases.

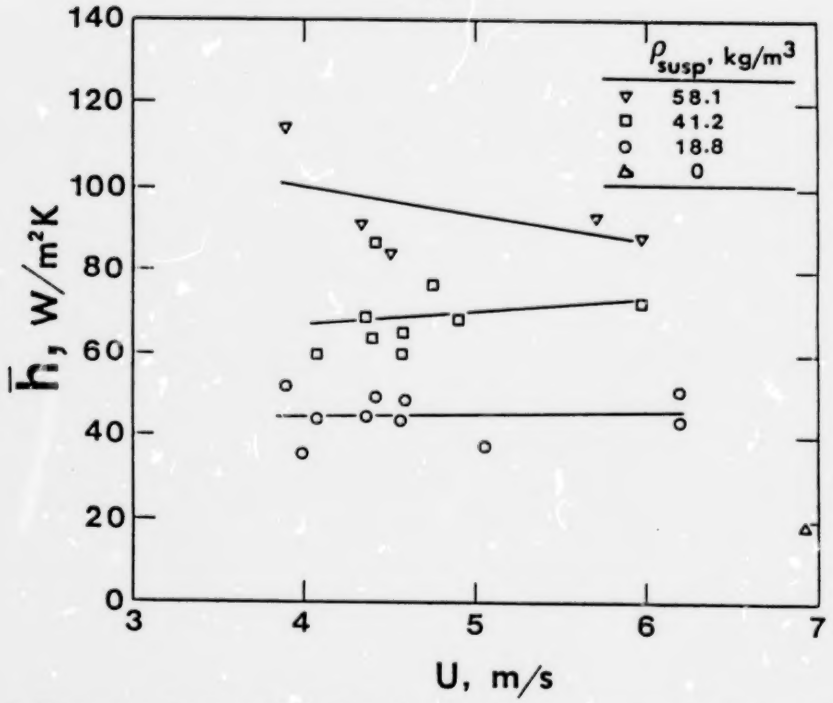


Fig. 8 - Influence of superficial gas velocity on average heat transfer coefficient at three suspension densities for the 188 μm sand

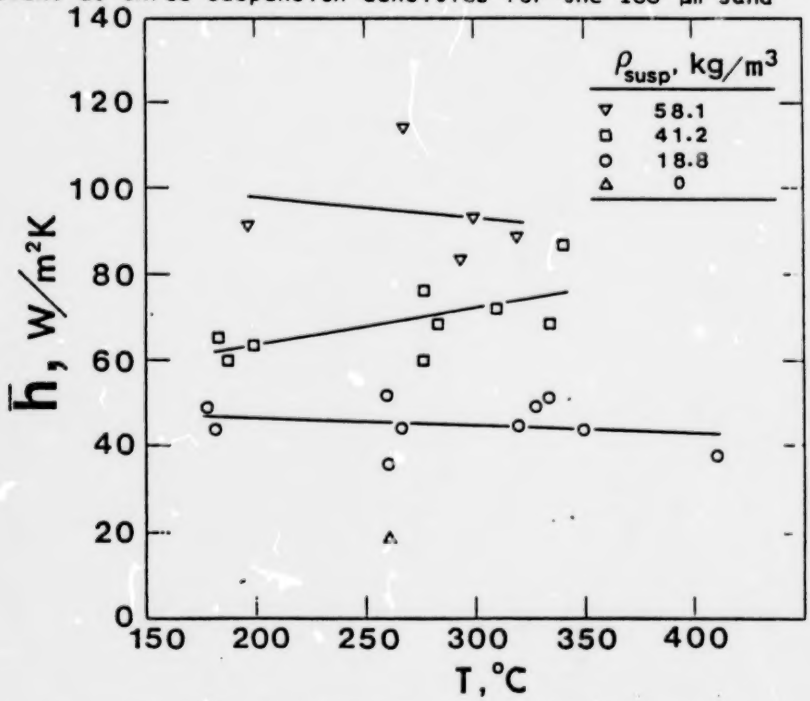


Fig. 9 - Influence of suspension temperature on average heat transfer coefficient at three suspension densities for the 188 μm sand

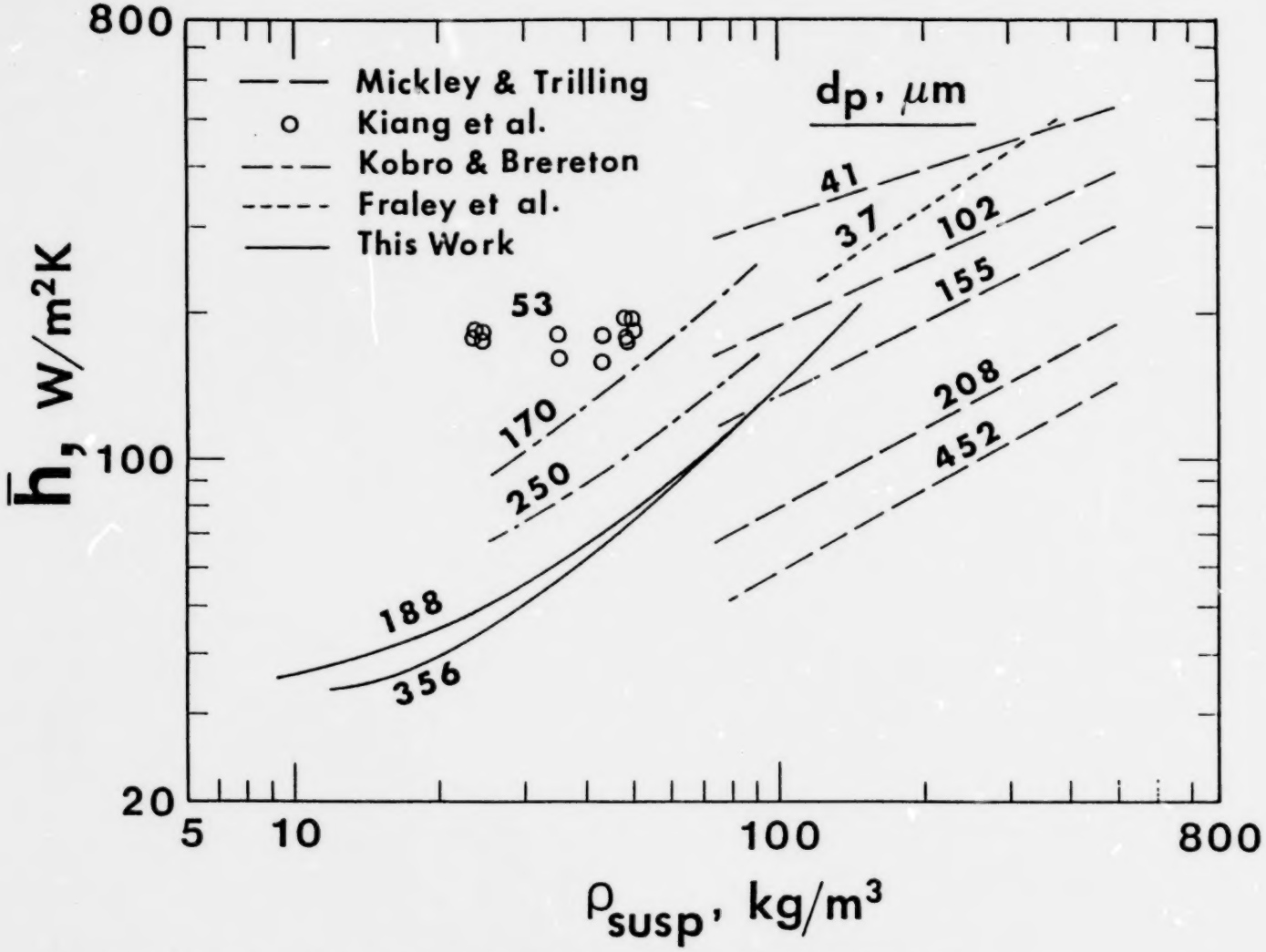


Fig. 10 - Comparison of experimental heat transfer coefficients obtained with the 1.53 m long heat exchange surfaces in the present study and earlier measurements of other workers for much shorter heat transfer probes (Mickley and Trilling, 880 mm; Kiang et al., 57 mm; Fraley et al., 150 mm; Kobro and Brereton, 100 mm).

5. COMMERCIAL FLUIDIZED BED INSTALLATIONS

by W.B. Alderton, P.Eng., Polymath Energy Consultants Ltd., Vancouver

Practical applications of FBC technology and hardware available from equipment vendors and manufacturers were discussed. The presentation focussed away from technical details and onto the broader picture to show how specific technical aspects were incorporated in commercial units.

Bubbling bed FBC units were described, including small Babcock Worsley FBC furnaces, Babcock Power "Fluidburn" boilers, Foster Wheeler, Fluidyne and M.E. boilers. Sizes ranged from 0.6 to above 300 MWth.

CFBC units were discussed, and the relative advantages and disadvantages of FBC versus CFBC boilers were also examined. CFBC units were described including Pyropower, Lurgi, Studsvik, VKW "Circofluid", and Gotaverken boilers.

A list of in-service large and small FBC and CFBC boilers can be obtained from Polymath Energy Consultants Ltd.

6. DESIGN AND OPERATION OF THE UBC PILOT SCALE CFBC UNIT

by Prof. C.J. Lim, University of British Columbia

The UBC circulating fluidized bed combustion unit was designed as a flexible combustor for burning a wide variety of fuels and to allow fundamental data to be obtained, as well as practical test data on combustion conditions. A schematic diagram of the equipment is given in Fig. 11. The equipment is located in the high headroom lab of the new UBC Pulp and Paper Centre and features:

Reactor dimensions:	0.15 x 0.15 x 7.32 m high
Primary air distributor:	3 tuyeres, each with three orifices, sloping downward at 30° to the horizontal
Secondary air:	4 ports 0.9 m above the distributor plate with either 2 opposed jets or swirl configuration
Solid fuel feeding system:	large hopper, rotary valve, screw feeder
Sorbent feeding system:	small hopper, rotary valve, screw feeder
Liquid fuel feeding:	barrel heaters, rotary pump, traced lines atomizer

Heat removal: two membrane surfaces, each consisting of 0.3 m^2 heat transfer area on one wall or wall or one internal cooling tube 1.2 m long; off-gases cooled by heat exchanger.

Particle removal and recycle: refractory lined primary cyclone returning solids via standpipe and L-valve; secondary cyclone with optional recycle; bag-house to be installed.

Preheating system: natural gas or propane to preheat incoming primary air.

Instrumentation: thermocouples, pressure taps and view ports at frequent intervals; off-gases analyzed by on-line oxygen, SO_2 and NO_x analysers; CO, CO_2 and hydrocarbons analyzed by gas chromatography.

Additional details of the equipment are given elsewhere (6.1). The unit was started up in August 1986 beginning with pure heat transfer runs (6.2). Fuel trials were started in November. Preliminary results are given elsewhere (6.3, 6.4). Copies of references were available at the workshop. By the date of the workshop more than 300 h of tests had been completed using three different coals, pyrolysis-derived char, hog fuel, sawdust, fuel oil and a residual hydrocarbon.

References

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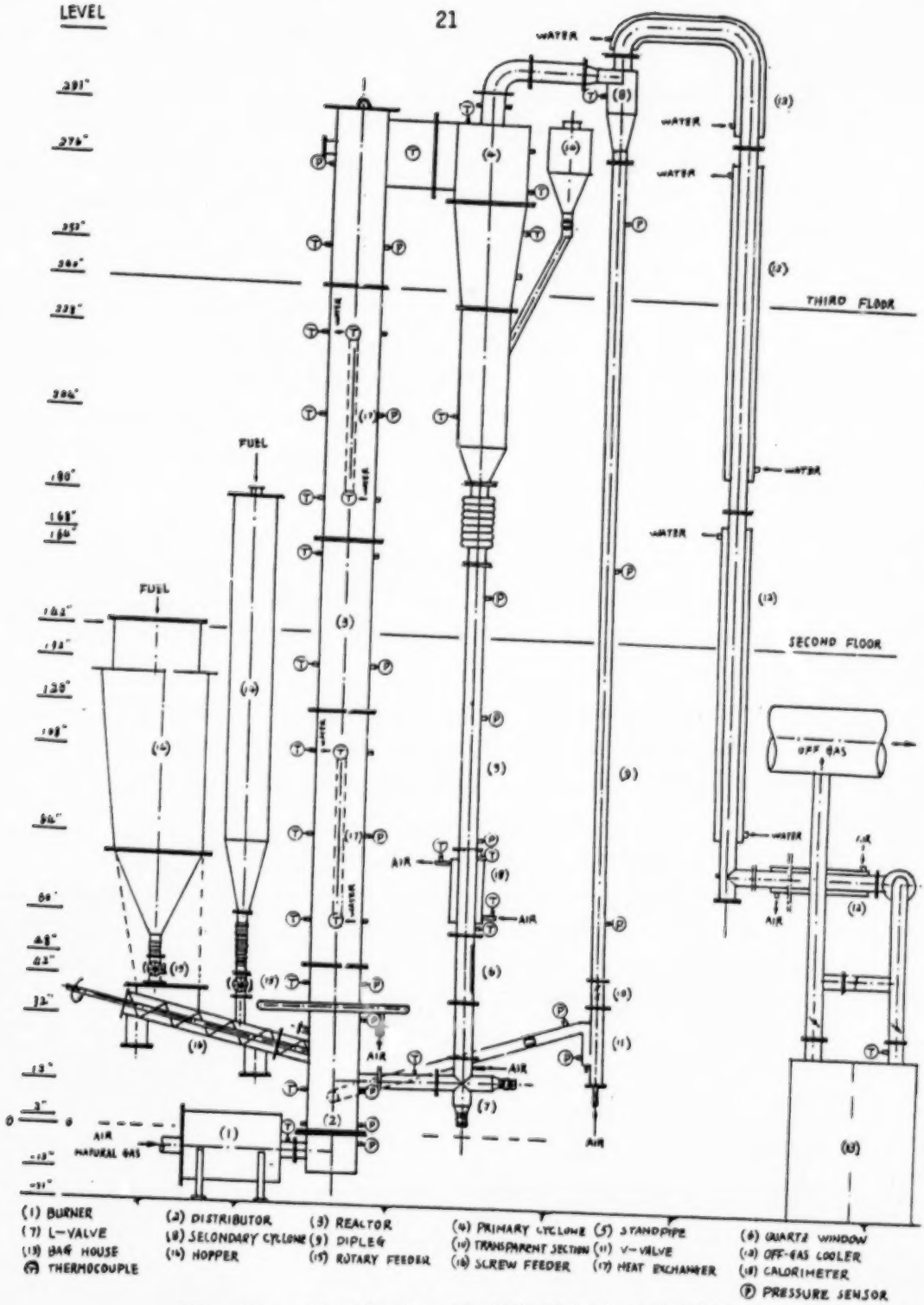

Fig. 11 - Circulating fluidized bed combustor

7. NO_x AND SO_2 EMISSION FROM CFBC UNITS

by Jiansheng Zhao, University of British Columbia

The UBC pilot-scale CFBC unit is equipped with various on-line gas analyzers including those for NO/NO_2, SO_2 and O_2. Gas samples can also be taken to determine CO, CO_2, SO_2 and unreacted hydrocarbon concentrations by gas chromatography.

Preliminary results using a high sulphur Eastern Canadian (Minto) coal indicate that fairly high sulphur capture was achieved (Fig. 12) in spite of the poor quality of the limestone (Elmtree). NO_x emissions were 110-150 ppm (Table 1). Woodwastes were found to have lower NO_x emissions than coal presumably due to lower nitrogen content. Changing the secondary to primary air ratio had surprisingly little effect on NO_x emissions.

The effects of factors such as limestone size, bed temperature and solids circulation rate on sulphur capture and secondary to primary air ratio, excess air and Ca/S ratio on NO_x emission will be investigated further. A multi-position gas sampling line will be installed to determine gas composition along the bed height. The profiles generated will help to develop a reliable reactor model for CFB combustion which makes allowance for sulphur capture and NO_x generation and reduction.

Table 1 - NO_x emissions for various fuels

Fuel	T(C)	U(m/s)	sec/prim	Excess air (%)	NO_x(ppm)
Minto coal	830-880	7-10	0.5-1.5	10-20	110-150
Hydrocracking Pitch	850	7.6	0.5	20	140
Sawdust	850	7.6	1.1	20	85
Hogfuel	870	7.6	0.7	20	80

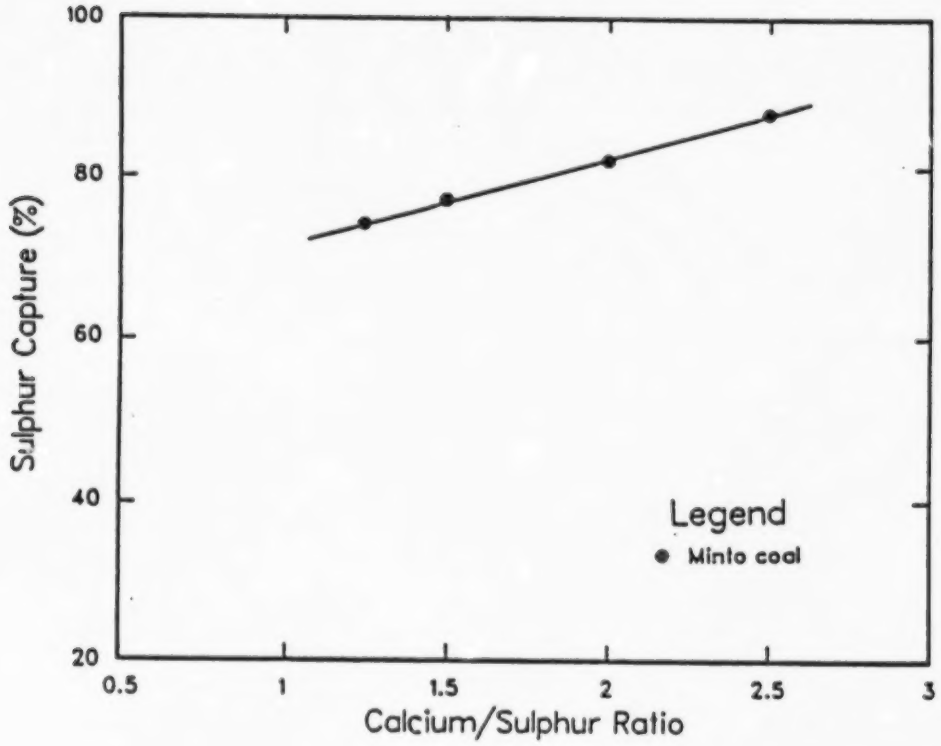

Fig. 12 - Sulphur capture vs Ca/S molar ratio for Minto coal/Elmtree limestone: bed temp 860°C; sup. velocity 7 m/s; sec/primary air ratio = 1.1; excess air = 20%.

8. COMBUSTION OF SYNCRUDE COKE WITH SULPHUR CAPTURE BY LIMESTONE IN A 100 mm DIAMETER CFBC

by D. Liang, Mineral Sciences Laboratories, CANMET

A brief overview of FBC related research activities at the Mineral Sciences Laboratories was given . The presentation focussed on results from a recent study on the combustion of Syncrude coke with Fort McMurray limestone as sorbent in a small-scale CFBC. The objective was to determine the sulphur and metals capture efficiencies and to assess the potential for corrosion in a CFB environment.

The results indicate that good sulphur capture of 90% can be achieved with a Ca/S ratio of 2.0 and the capture of the vanadium and nickel by bed solids is also good at 88% and 93%, respectively. Further examination of the uncooled SS 304 probes placed in the combustor showed signs of sulphidation/oxidation attack under ash deposit, similar to that found in some AFBC units.

A significant amount (25%) of the limestone was found to leave the combustor uncalcined due to its very fine size. The following recent publications were distributed:

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9. EFFECT OF COAL TYPE ON COMBUSTION IN AN ATMOSPHERIC FLUIDIZED BED COMBUSTOR by H.A. Becker, Queen's University, Kingston, Ontario

Trials on the burning of a Western Canadian subbituminous coal (Highvale) were performed in an atmospheric fluidized bed combustion (AFBC) pilot plant (bed area 0.155 m^2). Conditions were: mean coal particle diameter 10.6 mm; fluidizing velocity 1.1-3.1 m/s; excess air 1.7-55%; recycle ratio (fraction of cyclone catch recycled) 0-0.95; bed temperature 750°C-950°C. The bed of sand had a 0.6 mm mean particle diameter. The combustion efficiency as measured by carbon burn-up was 98-99.6%. An empirical correlation relates overhead carbon loss to operating variables. Comparison with correlations from trials on Eastern Canadian bituminous coals indicates that free swelling index is an important fuel characteristic affecting overhead carbon loss in AFBC systems. Since the bed was of sand, calcium entered only through the mineral matter of the coal. Because of its low sulphur and high shale contents, the coal alone provided a high Ca/S mole ratio of 3.7. The observed sulphur capture was 80-99% when operating with underbed fuel injection and decreased to 50-95% with overbed injection.

The report describing this work can be obtained from Dr. E.J. Anthony, CANMET or from Dr. H.A. Becker, Queen's University.

10. HOT GAS CLEANING

by Prof. Roland Clift, Dept. of Chemical Engineering, University of Surrey, Guildford, England (Visiting professor at the University of British Columbia)

Power generation by means of pressurized fluidized bed combustion and combined cycle gasification processes both require that gases be cleaned at high temperatures and pressures (typically 800-900°C and 10-20 bars) in order to assure maximum efficiencies. Techniques for hot gas cleaning include cyclones, electrostatic precipitators and filters. Whereas cyclones work well at high temperatures, generally they are unable to assure sufficient removal efficiencies, especially under process upset conditions, to protect gas turbines. Electrostatic precipitators have serious material problems and cleaning, (e.g., cleaning by rapping may be a problem, especially for gasification char). Developments in ceramic filters have led to bag-type and candle-type filters. Whereas the bags have tended to give severe problems, the candle-type filters offer the best short term prospects for high efficiency cleaning at high temperatures.

Work is in progress at the University of Surrey on a fluidized bed filter. Aerosol particles are captured on larger granules which can then be transferred continuously to a separate vessel where cleaning can occur. A binding agent is required to cause the small particles to be retained by the larger ones. Cracking of heavy fuel oil can provide the binding agent under some circumstances. Work is also in progress on ways to remove alkalis from high temperature gases. This is more of a problem in the UK than in North America where coals tend to have low alkali contents.

11. FLUIDIZED BED RESEARCH AT THE TECHNICAL UNIVERSITY OF NOVA SCOTIA

by F. Hamdullahpur, Centre for Energy Studies, Technical University of Nova Scotia

A theoretical and experimental study was conducted to determine the flow behaviour of gas and particulate phases above the bed surface. It was concluded that the gas bubbles erupting at the bed surface maintain their existence in the form of turbulent eddies, so called "ghost bubbles" (Kehoe 1972, Pemberton and Davidson 1983, Hamdullahpur and MacKay 1985).

Based on this study, a separate research program has been undertaken to study the behaviour of secondary swirling air injection in the freeboard. The swirling secondary air is expected to break the ghost bubbles thus enhance gas-gas mixing in the freeboard. The effects of swirl number, primary to secondary air rate, orientation, and location of injection are being investigated.

Combustion of coal water slurry (CSW) fuel for small scale applications is being investigated. Combustion characteristics of CWS, effect of droplet size, evaporation and devolatilization of CWS, effect of bed material, sulphur retention, second stage air injection and post combustion in the freeboard, and scale up studies have been investigated. Based on the results from a 35 kW unit, a sucessful scale up to a 105 kW unit was achieved. Future work will include scaling and fabrication of 250 kW and 1 MW unit for light industrial and on-site waste incineration applications.

Circulating fluidized bed research

Research is directed towards: heat transfer at high temperatures; burning rate, mass transfer and attrition of carbon particles; combustion and sulphur capture; automatic control; effect of scale up on hydrodynamics and burning characteristics; burning efficiency of various types of fuels; measurement of solid circulation rate; and design and construction of an industrial size CFB.

12. TUBE EROSION IN BUBBLING FLUIDIZED BEDS

by Jingxu (Jesse) Zhu, University of British Columbia

Horizontal tube erosion tests were carried out in a three-dimensional fluidized bed with a cross-section of 218 x 206 mm and 1.52 m high. Sample rings of different materials were mounted on a solid bar and were weighed before and after each test. The erosion rates based on unit area were then calculated from the weight loss. Different factors were tested:

(1) Silica sand from 0.44 to 1.68 mm diam at 1.4 m/s velocity keeping U-Umf = 1.4 m/s. The results showed that the erosion rate increased as the particle size was increased. A linear relationship was found between erosion and particle size between 0.6-1.5 mm.

(2) Gas superficial velocity was varied from 1.0 to 2.5 m/s using 1.0 mm silica sand . Again, erosion rate increased linearly as velocity was increased.

(3) At 1.9 m/s velocity, using silica sand (1.0 mm) as the eroding particles, and four different tubes it was found that the tube and erosion rate remained roughly the same except for the smallest (15 mm diam) which had a dramatically higher rate.

(4) Ten different materials were used to make sample rings. Six different mechanical properties of the materials were considered. Tube material hardness appeared to have little effect on tube erosion rate, although Young's modulus played a very important role. The erosion rate increased as the Young's modulus decreased. This may be because the low velocity of particles in the bed (1.0-6.0 m/s) most of the time can only cause elastic deformation instead of the plastic deformation caused by high velocity particles (-100 m/s).

(5) Some rings were cut into small segments to determine the "local" erosion rate. It was found that over 95% of the erosion occurred over the bottom part of the tube with the maximum erosion rate 40-50° from the bottom.

Additional tests will be carried out. Different particles will be used and a dropping device is being built to test various factors under a "controlled environment".

13. ENVIRONMENT CANADA'S RESEARCH PROGRAM ON FLUIDIZED BED COMBUSTION

by G.A. Ross, Environment Canada

Control of acid rain is a major priority for Environment Canada (EC). Because FBC technology has the potential to control SO_2 and NO_x emissions, EC is keenly interested in environmentally-focussed research which will contribute to the development and implementation of this technology in Canada.

FBC Research Program

Since 1981 the Oil, Gas and Energy Division of EC has conducted FBC research funded by the Federal Interdepartmental Panel on Energy Research and Development (PERD). In recent years the funding has been in the order of $150K/a. The goals are:

1) to identify potential environmental concerns at an early stage in the development of FBC technology in Canada, and
2) to develop and demonstrate environmental protection practices and technologies applicable to FBC.

Environmental protection measures will be incorporated into a series of Federal Environmental Codes of Practice for Steam Electric Power Generation (SEPG). A Design Phase SEPG Code was published in 1985, and other codes in the series will follow. These codes have no legal status, but make recommendations concerning reasonable and practical measures that can be taken at steam electric power facilities to preserve the environment. They may be used by various federal agencies, the provinces, the electric power industry, and the public as sources of technical advice and guidance.

Environmental Concerns

Environment Canada is concerned that solving one problem does not lead to unwanted or unexpected environmental side effects, e.g., that the abatement of air pollution does not lead to unacceptable liquid or solid waste problems. General concerns relating to FBC and similar technologies are:

- wastewaters generated during boiler operation, processing of solid waste and equipment washing,
- land use/reuse at solid waste disposal sites,
- dusting from solid waste disposal sites,
- contamination of surface runoff or groundwater by contaminants leached from solid waste

Preliminary studies of FBC waste characteristics have resulted in the following specific concerns:

- large volume of solid wastes produced,
- reactivity of the wastes may lead to handling problems and impair the physical integrity of landfill waste,
- landfill wastes may be susceptible to dusting and the dust may be irritating if inhaled, and
- leachates may have high pH and high dissolved solids concentrations

Description of Work

Early work in the program consisted of assessing the environmental implications of FBC and characterization of wastes from pilot units and from the FBC boiler at the Canadian Forces Base, Summerside, PEI. Publications generated from this work are listed below. Work in progress includes the Chatham solid waste disposal study, and a study being conducted by the National Hydrology Research Institute in Saskatoon to physically model the effects of landfill FBC waste on an aquifer.

Funding has been allocated to fiscal year 1989/90 and a proposal has been made to continue to fiscal year 1991/92. Projected work includes:

- follow-up field trials and long term monitoring at the Chatham solid waste disposal site,
- development of protocol for characterizing FBC wastes,
- investigation of FBC waste utilization,
- characterization of wastes from FBC of coke, tar, pitch, etc.
- a study of options for treatment of FBC wastewaters/leachates,
- documentation of air emissions control experience with FBC in Canada,
- publication of recommended practices for environmentally appropriate handling, disposal and utilization of FBC solid wastes

Coordination of Research

A major activity of the FBC Technology Environmental Advisory Committee (TEAC) is to identify needs relating to environmental aspects of FBC and to recommend appropriate research. The TEAC is composed of representatives from federal government agencies, major electric utilities and provincial environmental agencies. It is chaired by Environment Canada.

ENVIRONMENT CANADA PUBLICATIONS AND CURRENT STUDIES ON FLUIDIZED BED COMBUSTION - MAY 1987

EPS 3-WP-82-2 Pollution Control Implications of Fluidized Bed Technology for Coal-Fired Steam Electric Power Generation, CH_2M Hill Canada Ltd. for the Water Pollution Control Directorate, Ottawa, 1982, 114 p.

EPS 3/PG/2 — Preliminary Evaluation of AFBC Solid Waste Properties, 1982/83 by Dearborn Environmental Consulting Services and the Wastewater Technology Centre, Environment Canada, Ottawa, 1985, 101 p.

EPS 3/PG/6 — Treatability of Wastewaters from High CaO and $CaSO_4$ Content FBC Wastes by Dearborn Environmental Consulting Services for Environment Canada, Ottawa, 1986, 74 p.

EPS 3/PG/7 — Evaluation of Solid Residues from Atmospheric Fluidized Bed Combustion, 83/84 by Dearborn Environmental Consulting Services and the Wastewater Technology Centre, Environment Canada, Ottawa, 1986, 90 p.

EPS 3 PG/8 — Evaluation of Solid Residues from Atmospheric Fluidized Bed Combustion, 84/85 by the Wastewater Technology Centre, Environment Canada, Ottawa, 1986, 62 p.

EPS 3/PG/10 — Unique Management Characteristics of Bubbling Atmospheric Fluidized Bed Combustion Residues by M.M. Dillon Ltd. for Environment Canada, Ottawa, 1987, 96 p.

COMPLETED MARCH 1987 — Prediction of Wastewater Characteristics from Alkaline Combustion Wastes by Dearborn Environmental Consulting Services for Environment Canada.

IN PROGRESS — Technical Options for the Disposal of Circulating Fluidized Bed Combustion Solid Wastes

Other Relevant Publications

EPS 1/PG/1 — Environmental Codes of Practice for Steam Electric Power Generation - Design Phase, Environment Canada, Ottawa, March 1985, 85 p.

14. CHARACTERIZATION AND DISPOSAL OF CFBC SOLID WASTES

by R. Kissel, Dearborn Chemical Co. Ltd., Mississauga, Ontario

One limitation of the CFBC process is when adding limestone for sulphur capture the potentially large volumes of wastes will need to be safely handled and disposed of by landfilling. The results of a recently completed study for Environment Canada were described which was conducted to identify operational and environmental suitability of disposal options for wastes from a utility scale CFBC unit. Combustion tests were conducted using the UBC pilot plant to generate residues for characterization. These included tests to determine the physical, chemical, geotechnical and leaching characteristics of the residues.

The residues were found to be composed primarily of $CaSO_4$, CaO and silica/silicates. Lesser concentrations of trace elements derived from the coal ash were also quantified. The leachates were alkaline with pH about 12.6 and contained high TDS concentrations; mainly sulphate, alkalies and calcium. Low concentrations of metals were found primarily due to the high pH. The residues behaved as soil-like materials requiring about 20% moisture to achieve maximum dry unit weight of about 1.5 Mg/m^3.

The unconfined strengths of the residues, even after curing, were low - about 150 kPa. However, in a confined situation the strengths were much greater. Compaction like curing decreased the permeability of the optimally conditioned samples. Greatest reductions in permeability were achieved by subjecting the residues to freeze-thaw cycling. Results indicate that the residues must be conditioned by adding water and compacting for optimal disposal by landfilling.

15. DEVELOPMENT OF A GENERAL MODEL FOR FLUIDIZED BED COAL COMBUSTION

by Fernando Preto, Energy Research Laboratories, CANMET, EMR

Studies at Queen's University's FBC laboratory were undertaken to develop a mathematical model for fluidized bed combustion which would include all the significant processes occurring in a fluidized bed, and yet not include so much detail that a numerical solution would be either unworkable or too costly. It was recognized that at the current state of understanding a "complete" model was impossible, therefore some approximations were necessary. The desired model should also be amenable to changes, i.e., if a more accurate sulphur capture model were to be

developed it should easily be incorporated. The model of Becker, Beer and Gibbs was chosen as the basis for the Queen's model as it outlines a relatively simple framework which lends itself to a modular approach (1). Therefore, as a greater understanding of each process becomes available, the algorithm for that process can easily be replaced.

Model Development

The FBC model proposed by Becker, Beer and Gibbs is based on the two-phase model for bubbling fluidization. This model visualizes a swarm of solids-free bubbles travelling through a particulate "emulsion" phase. The two-phase model assumes that the fluidizing gas in excess of that required for fluidization bypasses the bed in the form of bubbles. In the development of the FBC model, the following additional assumptions were made:

(a) insofar as combustion is concerned, inert particles constitute the bulk of the material in the bed,
(b) particle mixing is such that the emulsion is effectively uniform in temperature,
(c) the combustor and therefore, the bed, are of uniform cross-sectional shape and area,
(d) gas flow is statistically uniform over the combustor cross-section, and mean values of local gas properties in the bubble and emulsion vary only with height above the base of the bed.

The mass balances for each phase include terms for the various effluxes occurring within that phase. These include coal combustion, sulphur capture, NO_x reduction, homogeneous gas phase reactions and interphase transfer. In the freeboard, particle composition and temperature are assumed to be uniform over the combustor cross-section, and mean local properties vary only with height above the top of the bed.

The combustion of coal was modelled in three stages: heating and drying, devolatilization, and char combustion. The devolatilization and char combustion interact to an unknown extent. The level of interaction depends on the rank of fuel fired, and large particles have both stages occurring simultaneously. In this study, the two stages were treated as though they occurred consecutively.

The sulphur capture model was based on the assumption that the sorbent is well mixed throughout the emulsion, and that the concentration of SO_2 is constant throughout each horizontal integration level. The model basis was that pore plugging leads to an exponential decrease in the sulphur available for SO_2 capture.

The NO model was developed by considering a number of competing processes - the level of fuel nitrogen converted to NO is due to a combination of NO forming and reducing processes. NO is generated by combustion of both volatiles and char. NO is reduced by reactions with nitrogenous fragments in the volatiles and by heterogeneous reaction with char.

A common approach to modelling gas phase reactions is to assume complete combustion in the presence of excess oxygen. However, if one considers the species known to be present in a combustor,

$$CO \quad CO_2 \quad CH_4 \quad H_2 \quad H_2O \quad O_2 \quad N_2 \quad NO \quad NO_2 \quad SO_2 \quad SO_3,$$

the complete combustion approach is inadequate. Gibbs' function minimization techniques were chosen to carry out equilibrium calculations since no specific reactions need to be considered for a solution. The particular derivation chosen for this study was the RAND variation of second-order non-stoichiometric algorithms.

Results and Discussion

A numerical simulation of the model has been developed and consists of a main program, MODFBC, and 58 subroutines. The computational algorithm is based on finding the coal feed rate necessary to satisfy the steady state energy balance at a given bed temperature. The computer programs were written in FORTRAN to run on the Queen's University Computing Centre's IBM 3081-G24 computer.

The predictions of the model have been compared with data from experiments carried out in an FBC pilot plant. The trends predicted by the model appear to be realistic, and agree with those obtained experimentally. Variations in the accuracy of the predictions were largely due to difficulties in estimating char attrition and elutriation, and to a limited knowledge of the processes occurring in the splash zone.

IEA Workshop Results

At an International Energy Agency (IEA) meeting held in London in 1984 and at a subsequent meeting held in Paris in May of 1985 the mathematical

model described herein was presented to IEA members. Interest in running the computer program was expressed by a number of members to whom tape copies of the program were then distributed. Aside from minor differences due to the use of different computers, most investigators had no difficulty in running the program.

At a meeting in Vienna (IEA AFBC Workshop on Mathematical Modelling, Vienna, May 5, 1986) several participants made an evaluation of the model. G. Brem of TNO in Holland presented a study wherein the calculation results of the model were compared with those of experiments carried out with the 4 MWth AFBC of TNO. The study concluded: "The results of the validation show that the qualitative prediction of the model is good. To increase the quantitative prediction more experimental results will be needed; especially profiles of the gas concentrations in the installation will be needed". A conclusion of the Vienna meeting was that "after minor modification of the program it was found that the model could represent measurement data fairly well".

At subsequent meetings (IEA AFBC Workshop on Mathematical Modelling) in Liege (November 7, 1986) and Boston (May 2, 1987) additional studies were reported. A few modifications have been made to the model and it has been converted to run on "IBM PC" type microcomputers.

In summary, IEA researchers have successfully run the mathematical model developed in this study. In most cases, reasonable agreement was found between the model predictions and experimental results. It is recognized that further submodel development is necessary, e.g., sulphur capture and freeboard processes. However, accurate modelling in most cases depends on obtaining additional experimental data.

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16. ENVIRONMENTAL ASPECTS OF FLUIDIZED BED COMBUSTION

by E.J. Anthony, Energy Research Laboratories, CANMET, EMR

Bubbling bed AFBC solid residues are unlike wastes produced by pulverized coal combustion (16.1). They resemble the wastes produced by Flue Gas Desulphurization (FGD) systems except they are dry and contain lime and calcium sulphate in anhydrous forms together with minor and trace inclusions of the elements normally found in coal ashes and limestone. From the point of view of disposal, they present dust problems similar to fly ashes, have potential for water pollution similar to FGD wastes and are somewhat more caustic because they contain unhydrated lime. The free lime also causes the waste solids to react exothermically when they come into contact with water. Temperatures above 100°C have been recorded in the laboratory.

Work on utilization of these wastes has identified the following potential uses:

- agriculture,
- lime substitute in acidic wastes neutralization
- waste stabilizing agent in lime/pozzolan systems;
- low strength backfill applications (with or without portland cement);
- soil stabilization and soil cementing;
- asphaltic concrete aggregate.

The other class of solid AFBC wastes is circulating FBC residues. These have received considerably less study than bubbling bed wastes. However, they are expected to have less free lime and a smaller mean particle size but otherwise should be chemically and physically similar to

bubbling bed wastes. A recent Canadian Electrical Association (CEA) study (16.2) identified high concentrations of CaS (up to 6%) in the solid waste. Since CaS can produce H_2S, a hazardous gas, in contact with water this would adversely affect disposal costs and rule out utilization of the wastes for many potential applications (16.3). However, examination of the wastes from other CFBC units has suggested that the results observed in the CEA study were atypical, since the residues were obtained from a sub-scale rig with some design peculiarities. It appears that larger rigs produce residues containing negligible CaS concentrations providing solids are not withdrawn from regions under reducing conditions.

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Fluidized Bed Combustion Workshop
University of British Columbia, May 27, 1987

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